Measurement of friction coefficient on specialized duct tract

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Abstract: Proposed paper dealing with determination of pressure loss coefficient for air duct equipments. Measurement was performed at newly build track in Laboratory of Environmental Engineering, Tomas Bata University in Zln. At the beginning of the article is definition of fan track with two options of flow direction available. This is followed by description of accesible volumetric flow control alternatives. In the article is described calculate method of minor loss coefficient from standard ISO 7235. In the result section is presented findings with discussion about results for each measurement. Paper is concluded with outline for further research.

Key–Words: friction coefficient, air flow measurement, turbulence, pressure measurement, duct track

1 Introduction

Aerodynamic properties of air is in the scope of interest of researchers for more than a century. The air flow parameters were investigated by Hagen, Reyleigh, Reynolds [1], followed up by Prandtl, Moody [2], Colebrook [3], Von Karman [4] and many others. [5] The knowledge of concept properties concerning HVAC components is a prerequisite for successful design technique. In the draft of ventilation ducts, the pressure loss is an important parameter to know based on different velocities of transported air. Determination of parameters for specific HVAC devices are in scope of specialized laboratories. Laboratory of such capabilities is maintained by authors of this article at Tomas Bata University in Zlin, Faculty of Applied Informatics and is involved in this paper. Special interest in actual development is put on acoustic silencers for mounting in the ducts which is an important element within HVAC systems. With the silencers there are two main parameters which should considered. The first one is a sound attenuation the and second one is pressure losses. It is regrettable that these parameters are in opposition to each other. In the authors' facility, the Laboratory of Environmental Engineering, it is possible to test the silencers for both parameters and thus combine both parameters for better performances. In the presented paper, the focus is on measurement methods described by standard ISO 7235 [6] and comparison of results obtained by this standard with analytical calculations with different approach. Mainly, this standard lacks any details of how to accomplish such measurement of friction losses. Investigation of such procedure is a subject of the presented paper, where three possible ways how to execute the measurement are compared.

Firstly, the article describes the methods of measurement with the test track, and the description of calculation for losses by standard and alternative method. Above mentioned is linked with the description of the measurement method with characterization of used samples. Then the measured results are described, followed by discussion. The article is concluded by used methods and samples.

2 Methods

There is a possibility to measure minor loss coefficient of any equipment determined for installation inside a duct. For these measurements is used multiple-nozzle chamber to resolve flow rate through the duct configuration. There is a wall taping mounted on ducts for measurement of static pressure before and after surveilled object. Such measurements and consequential calculations are in scope of this article. This section will cover the description of the duct tract and two options for determination of minor loss coefficient. Firstly by ISO 7235 [6] and subsequently by hydraulic equation. The methods section ends with a brief summary of the samples.

2.1 Fan track

There are two available dimensions for the track. The diameters are $200mm$ and $400mm$. For each dimension there are available several types of duct which can be connected with each other. This function leads to many measurement variations. The track allows measurements of fan performance curve, loss coefficient, acoustic parameters, leakage and others. All components of the track are made in accordance with International standard ISO 5801. Controlling system of the track is handled by PLC with touch panel including visualization. All measured data are periodically saved to local FTP server in form of CSV file. The whole controlling board is depicted on Figure 1. On the left can be seen frequency converters for fans, next to these are buttons for switching circuit breaker, a touch panel with visualization for setting experiment and on the right is a computer unit. For the purpose of results evaluation was used an automated excel sheet, where a manually loaded data and all calculations are ensued by graphical output. The data collection is started after two minutes phase to get equilibrium conditions and then the data are collected every half of a second, for one minute. This means that for each point were collected 120 values which are time-weighted average afterwards.

The measurement track is depicted in Figure 2. The whole length without the sample is more than $9m$ long. There are two options to carry out the measurement. First one is at inlet side of fan. That track is at 2a and consists of inlet, ducts, sample, ducts, straightener, size extension, multiple-nozzle chamber (MNC), fan, duct and outlet. Ducts before MNC is of diameter $200mm$, tract after MNC are of dimension $400mm$. Second option is 2b and is at outlet side of fan, lengths are similar as previous and only difference is in sequence of parts.

2.2 Minor loss coefficient by CSN EN ISO 7235

In the following text will describe a method to measure minor loss coefficient by international standard ISO 7235. [6] This norm is mainly used for duct silencers and describes the measurement of sound attenuation as well as the measurement of minor loss coefficient. Evaluation of friction coefficient is done by subtracting the pressure difference at substituted duct from static pressure difference of silencer. All computational steps are described by following equations.

Figure 1: Controlling board for duct tract

$$\Delta p_{tot} = p_{s1(I)} - p_{s1(II)} \tag{1}$$

Where is	Δp_{tot}	total pressure	[Pa]
	$p_{s1(I)}$	pressure drop at measured device	[Pa]
	$p_{s1(II)}$	pressure drop of substituted duct	[Pa]

The value $p_{s1(I)}$ is the difference of static pressure between the measured sample. The value $p_{s1(II)}$ is the same as before only performed on substituted duct. There is also included measurement between static pressure before sample and atmospheric pressure $p_{s1(a)}$ only for graphical representation of results. In the following equations 2, 3 is shown how to calculate dynamic pressure and determine density of inlet air.

$$p_d = \frac{\varrho_{in}}{2} v^2 = \frac{\varrho_{in}}{2} \left(\frac{q_v}{A}\right)^2 \tag{2}$$

Where is	p_d	inlet dynamic pressure	[Pa]
	v	flow velocity	$[\frac{m}{s}]$
	A	area at the point of measurement of static pressure	[m]
	ϱ_{in}	density of inlet air	$[\frac{kg}{m^3}]$
	q_v	volumetric flow rate	$[\frac{m^3}{s}]$

$$\varrho_{in} = \frac{p_{s1} + p_a}{R\left(\theta_{in} + 273\right)} \tag{3}$$

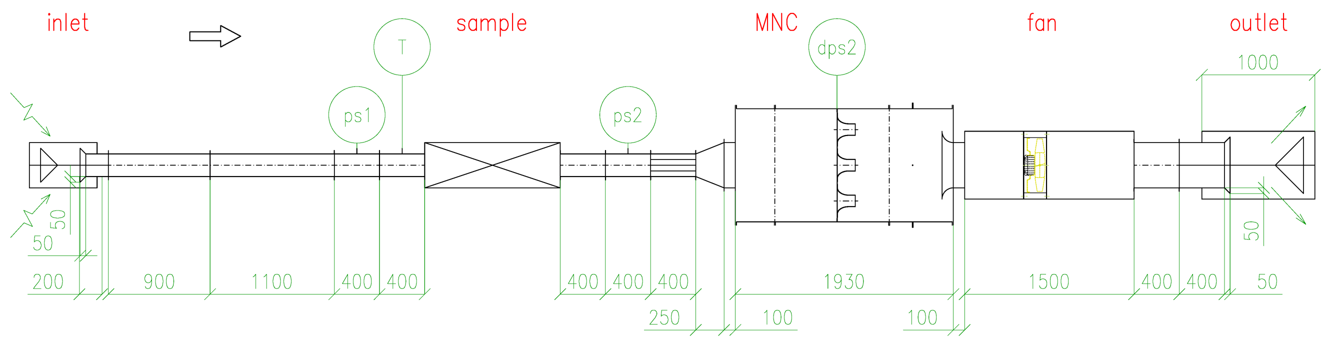
Where is	R	gas constant	$287[\frac{N\cdot m}{kg\cdot K}]$
	θ_{in}	temperature of air before sample	$[^{\circ}C]$

The coefficient of the total pressure loss ξ averaging over a range of flow rate is calculated from the equation (4).

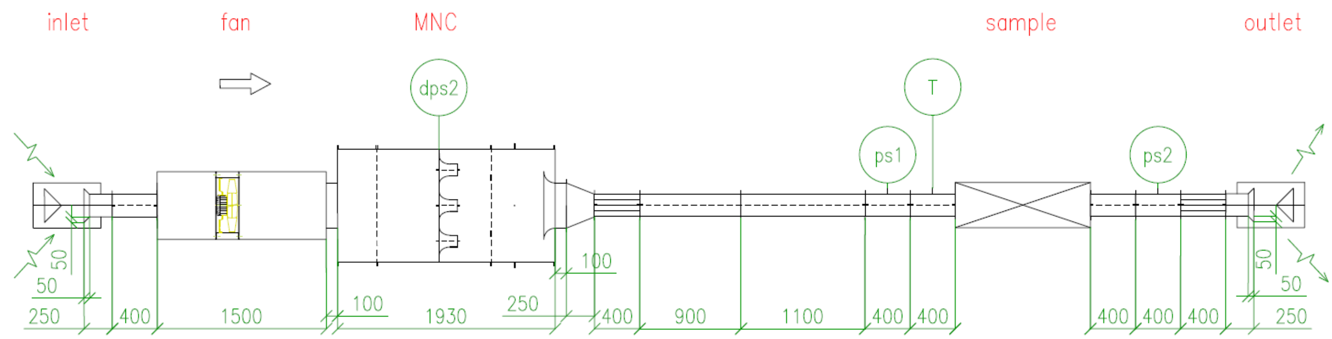
$$\xi_{iso} = \frac{\Delta p_{tot}}{p_d} = \frac{\Delta p_{tot}}{\frac{\varrho}{2}\left(\frac{q_V}{A}\right)^2} \tag{4}$$

Where is	ξ_{iso}	minor loss coefficient by ISO 7235	[-]
	A	area of duct	$[m^2]$

Mean loss coefficient is then calculated from equation (5).



(a) suction pressure



(b) discharge pressure

Figure 2: Track for measurement of friction loss coefficient

$$\xi_{iso,m} = \frac{1}{N}\sum_{j=1}^{N}\frac{p_{s1(I)j}}{p_{dj}} - \frac{1}{M}\sum_{k=1}^{M}\frac{p_{s1(II)k}}{p_{dk}} \quad (5)$$

Where is			
	N	number of measured points of silencer	[-]
	M	number of measured points of substitution	[-]

2.3 Minor loss coefficient from Bernoulli equation

Other option could be the determination of ξ from energy equation which is summarized in (6), which is known also as Bernoulli Equation.

$$p_1 + \frac{\rho v_1^2}{2} + h_1\rho g = p_2 + \frac{\rho v_2^2}{2} + h_2\rho g + \Delta p_{loss} \quad (6)$$

Where is			
	p	static pressure	[Pa]
	h	elevation height	[m]
	g	acceleration of gravity	$[\frac{m}{s^2}]$
	Δp_{loss}	pressure loss	[Pa]

The focus is now on Δp_{loss} which is specified by equation (7).

$$\Delta p_{loss} = \Delta p_\lambda + \Delta p_\xi \quad (7)$$

Where is			
	Δp_λ	major loss	[Pa]
	Δp_ξ	minor loss	[Pa]

The equation (8) summarizes the Darcy-Weisbach Equation for calculation of major loss and in equation (9) is noted the calculation of minor loss .

$$\Delta p_\lambda = \lambda\frac{l}{d}p_d = \lambda\frac{l}{d}\frac{\rho}{2}v^2 = \lambda\frac{l}{d}\frac{\rho}{2}\left(\frac{q_V}{A}\right)^2 \quad (8)$$

Where is			
	λ	friction coefficient	[-]
	l	length of the duct	[m]
	d	hydraulic diameter of duct	[m]
	p_d	dynamic pressure	[Pa]

Minor loss coefficient, also known as friction coefficient, is dependent only on Reynolds number for laminar flow. For turbulent flow matters the friction coefficient function of Reynolds number as well as the roughness of the duct. In 1937 Colebrook and White presented an experiment of friction coefficient in roughness duct and established Colebrook-White formula [7]. There are at least three implicit formulas known by today's literature. This article will present only the mostly known; thus authors of this article compared results with all the implicit equations and there have been negligible aberration in results. The used equation is formulated in (10) which presented Collebrook in 1939.[3][8] There have been many attempts to provide explicit form in the past. Mainly because iterative process of implicit equation was complicated in time when calculators were not invented. It would be possible to use so called Moody chart, which was laid out by prof Moody in 1944 as estimation from Colebrook-White formula. This chart made it easy to estimate friction coefficient and was extensively used by engineers for more than a half century. [2][8] This changed with invention of electronic chips and computers which ceased the problem with iterative process. [8]

$$\Delta p_\xi = \xi_{be} p_d = \xi_{be}\frac{\rho}{2}v^2 = \xi_{be}\frac{\rho}{2}\left(\frac{q_V}{A}\right)^2 \tag{9}$$

Where is ξ_{be} minor loss coefficient by Bernoulli equation [-]

$$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{2,51}{Re\sqrt{\lambda}} + \frac{\varepsilon}{3,7}\right) \tag{10}$$

Where is Re Reynolds number [-]
ε Roughness coefficient of duct [m]

So called Reynolds number was introduced in 1883 by Osborne Reynolds and it is transcribed in (11). Reynolds number came to known by usage of Sommerfeld and Prandtl at the beginning of the last century. [1][5]

$$Re = \frac{vd}{\nu} = \frac{\rho v d}{\mu} \tag{11}$$

Where is ν kinematic viscosity of the fluid $[\frac{m^2}{s}]$
μ dynamic viscosity of the fluid $[\frac{Ns}{m^2}]$

From above equation (7) could be determined minor loss coefficient ξ_{be} by simple mathematical extraction and it is equal to (12). Also (13) can be used, particularly because there is unknown roughness coefficient for the silencers so λ should be neglected.

$$\xi_{be,\lambda} = \frac{2\Delta p_{loss}}{\rho v^2} - \lambda\frac{l}{d} \tag{12}$$

$$\xi_{be} = \frac{2\Delta p_{loss}}{\rho v^2} \tag{13}$$

2.4 Measurement practice

Measurement was performed in accordance with ISO 7235 and flow determination by ISO 5801. [6][9] The standards specify tapping to obtain average static pressure. Before tapping should be straight duct in length at least $5d$ or two meters long, depending on which value is higher. It is also stated, that position of tapping should be $1,5d$ from entrance to tested object as well as at its exit. The measurement of temperature inside the duct is specified as $2d$ in front of the tested specimen. [6]

The standard ISO 7235 does not specify the method of reduction of flow, nor states if the measurement should be done in-front or behind the fan. So in this article the measurement was performed by both options. Due to the nature of the measurement tract it was possible to perceive three types of flow reduction. Description of those three flow control options and naming is as follows:

- **FanRedu** - Reduction of flow and static pressure is done by decreasing power of ventilator (this method could be persecuted from 100% to 20% of ventilator power, where selected steps for fan was by 10%).
- **OutRedu** - Reduction of flow and static pressure is done by throttling at outlet duct. Decreasing of flow was done based on FanRedu values of flow for comparison of results.
- **InRedu** - Reduction of flow and static pressure is done by throttling at inlet duct. Decreasing of flow was done based on FanRedu values of flow for comparison of results.

2.5 Specimens

Measurement was done on three HVAC samples and their description is underneath.

- **Sample1** - This sample is the most complicated one, it has square outside shape with round inside silencing part. Its outlet is made from 9 small connections of diameter $80mm$. For the purpose of measurement was created a reduction chamber with $0,2m$ diameter outlet to fit to the measurement tract. The whole length is $1,45m$ and outer dimensions are $250x500mm$.
- **Sample2** - This sample is round with centre body. Its length is $1,2m$ and outer diameter is $0,4m$.

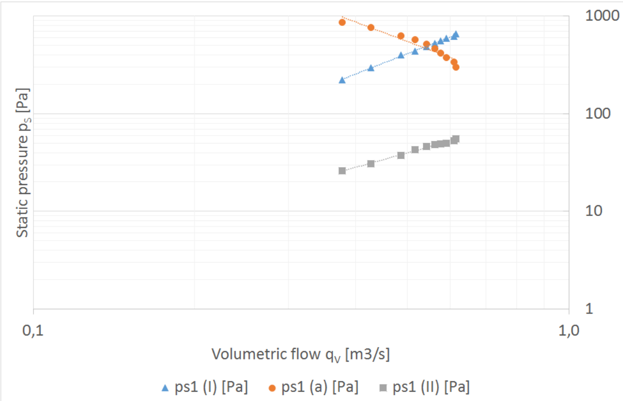


Figure 3: Log-log plot of inlet reduction for Sample1 by suction pressure

- **Sample3** - The last sample is the same as the first one, but outlet part with 9 connections is removed and it is directly connected to $0,2m$ fitting. The length is in this case $1,3m$.

3 Results

The following section contains results and findings gathered during the performed measurements. Firstly, it covers the InRedu method and its results, then results of OutRedu and FanRedu methods for all samples. All presented graphs are in log-log scale. This section concludes with a comparison of two types of calculations which were described in Methods section and introduction to option for backward finding of roughness coefficient.

3.1 Results for InRedu method by suction pressure

This method was tested only on Sample1 and is depicted in Figure 3. The method could be hardly used for appropriate presentation of results, nevertheless the minor loss coefficient was in the end similar as in other methods which will be presented.

3.2 Results for OutRedu and FanRedu methods by suction pressure

Pressure drop and flow through the duct with method OutRedu and FanRedu are depicted in Figures 4, 5 and 6. Difficulty during the measurement occurred when there was a necessity to measure substituted duct with the FanRedu method. When the measurement of substituted duct was executed, it should proceed with the same flow as sample which was at the beginning always around 60% with inequivalent steps.

Table 1: Comparison of methods with calculation by CSN for suction pressure

Sample	**Method**	$\xi_{csn}[-]$	**diff** $[-]$
Sample1	OutRedu	2,851	0,044
	FanRedu	2,808	
Sample2	OutRedu	2,598	0,054
	FanRedu	2,544	
Sample3	OutRedu	0,924	0,014
	FanRedu	0,911	

Table 2: Minimal and maximal Reynolds number for each sample and method for suction pressure

Sample	**Method**	**Re min** $[-]$	**Re max** $[-]$
Sample1	OutRedu	49 730	254 576
	FanRedu	89 678	257 955
Sample2	OutRedu	81 719	258 050
	FanRedu	76 512	258 035
Sample3	OutRedu	93 414	316 163
	FanRedu	95 922	317 042

The reason of this is due to steep losses of supplementary duct. This is reflected by the substituted curve, which has less points because fan can not go less than 20% of power. From the figures can be seen that both methods are similar and could be commuted. This fact is also digested in Table 1, where could be seen differences in methods by friction coefficient. The most significant difference in methods was $\xi = 0,054$ and occurred with Sample2, and is fractional number.

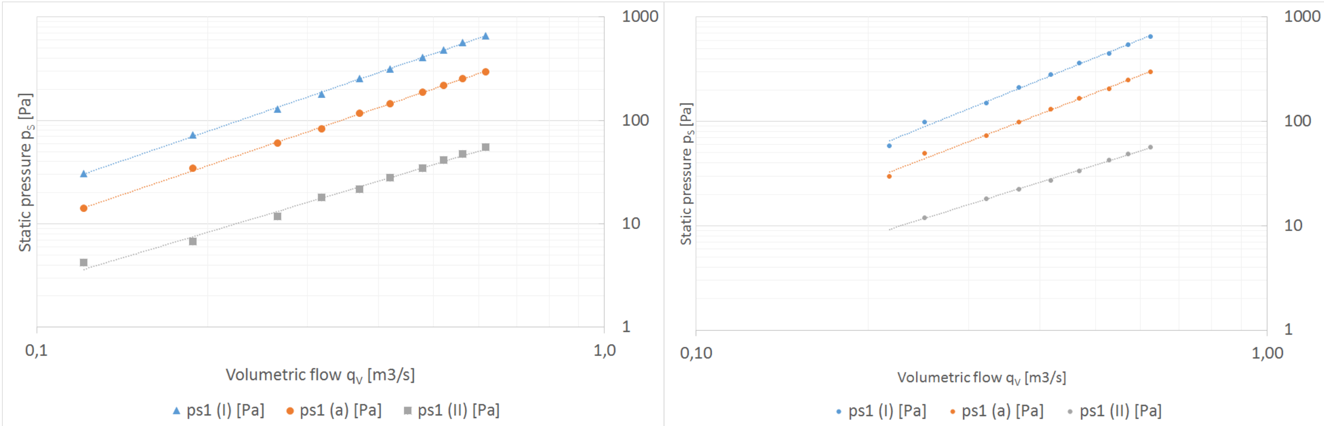
From the Table 2 can be seen that all flows were in turbulent region based on Reynolds numbers.

Results concerning calculation of ξ_{be} are recorded in Table 3, where the most significant difference with Sample1 is evident. The inequality with standard method is due to the fact that method measured by subtracting pressure with substituted duct could include inaccuracy.

In the Table 5 are compared two ways of calculation of ξ, namely equation (5) with (13). The difference is fluctuating around $0,3$. This diversity is mainly because in ξ_{csn} was taken total pressure subtracted by pressure of substituted duct as for opposition is taken only total pressure of sample for ξ_{be}.

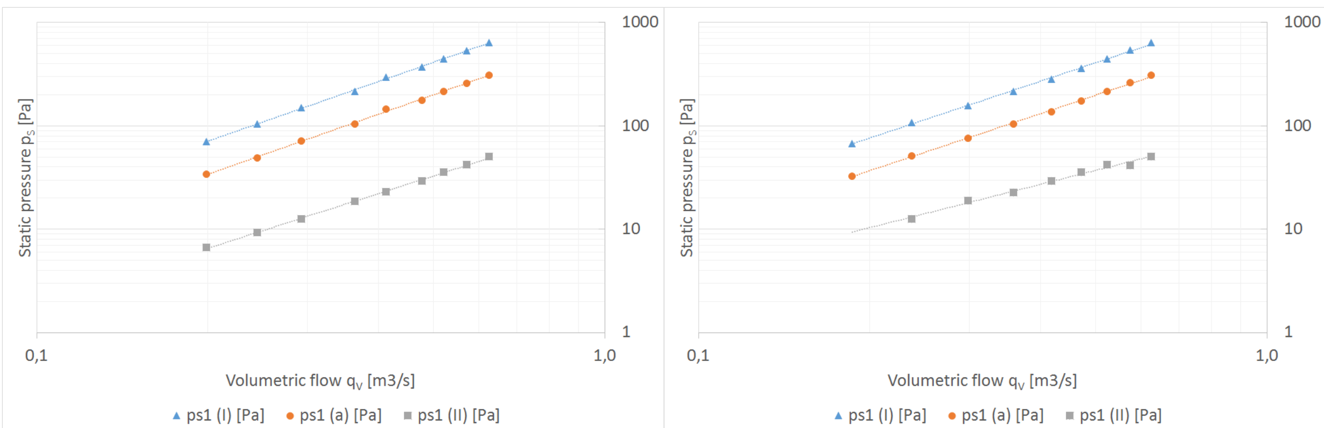
There are significant differences of coefficients within the used methods and samples. This is caused basically because there is difference in ξ calculated by both methods.

Table 4 summarizes all friction loss coefficients. First line is used for sample and method, thus S1-OR means Sample1 - OutRedu method and so on. In some



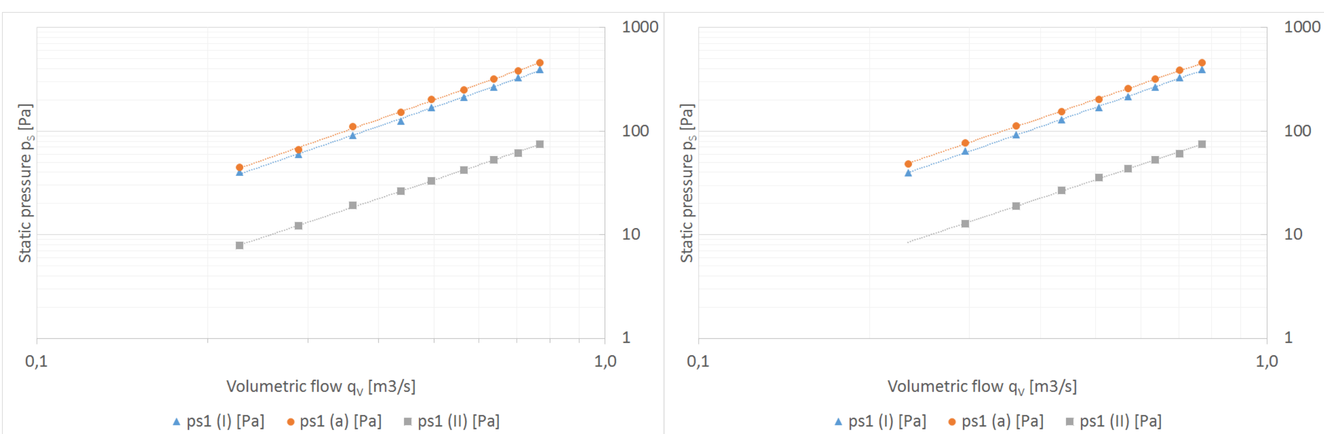
(a) OutRedu **(b)** FanRedu

Figure 4: Loglog plots for Sample1 by suction pressure



(a) OutRedu **(b)** FanRedu

Figure 5: Loglog plots for Sample2 by suction pressure



(a) OutRedu **(b)** FanRedu

Figure 6: Loglog plots for Sample3 by suction pressure

cases coefficients are missing, this is due to the nature of method where was low limit reached in different points. It is obvious that minor loss coefficient is independent on velocity inside the duct, this fact is valid

Table 3: Comparison of methods with calculation by BE for suction pressure

Sample	Method	$\xi_{be}[-]$	diff $[-]$
Sample1	OutRedu	3,099	0,117
	FanRedu	3,216	
Sample2	OutRedu	2,834	0,042
	FanRedu	2,876	
Sample3	OutRedu	1,154	0,007
	FanRedu	1,147	

Table 4: Match of loss coefficient for samples by method for suction pressure

S1-OR	S1-FR	S2-OR	S2-FR	S2-OR	S3-FR
2,6570	2,5516	2,5070	2,5112	0,8982	0,8987
2,7585	2,5658	2,5255	2,5225	0,9055	0,9030
2,7043	2,4402	2,5405	2,4592	0,8845	0,8917
2,7276	2,5009	2,5066	2,4307	0,8919	0,8848
2,7509	2,4317	2,7151	2,4446	0,9330	0,8731
2,8609	2,3580	2,5236	2,5303	0,8695	0,8971
2,7070	2,1497	2,7128	2,6119	0,9272	0,9442
2,7780	2,3227	2,6556	2,8450	0,9530	0,9925
3,1028	-	2,6998	-	1,0556	-
3,0284	-	-	-	-	-

only for velocity from 3 to $24\frac{m}{s}$. Thus in this range the measurements were executed. It would be interesting to accomplish measurement with velocity under the range achieved in this article.

3.3 Results for InRedu and FanRedu methods by discharge pressure

In this case the InRedu and FanRedu methods were used. The reason is that for OutRedu would be the same result as for InRedu in previous case due to nature of flow. For discharge pressure, the measurement was performed only for sample1. Graphs are depicted

Table 5: Comparison between option CSN and BE for suction pressure

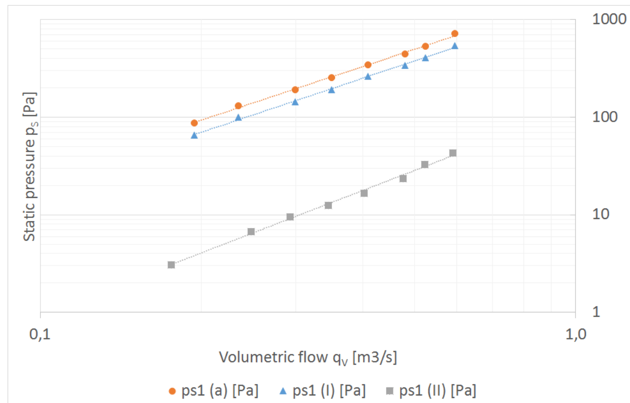
Sample	Method	$\xi_{csn}[-]$	$\xi_{be}[-]$	diff $[-]$
Sample1	OutRedu	2,851	3,099	0,248
	FanRedu	2,808	3,216	0,409
Sample2	OutRedu	2,598	2,834	0,236
	FanRedu	2,544	2,876	0,332
Sample3	OutRedu	0,924	1,154	0,230
	FanRedu	0,911	1,147	0,236

Table 6: Comparison of methods with calculation by CSN for discharge pressure

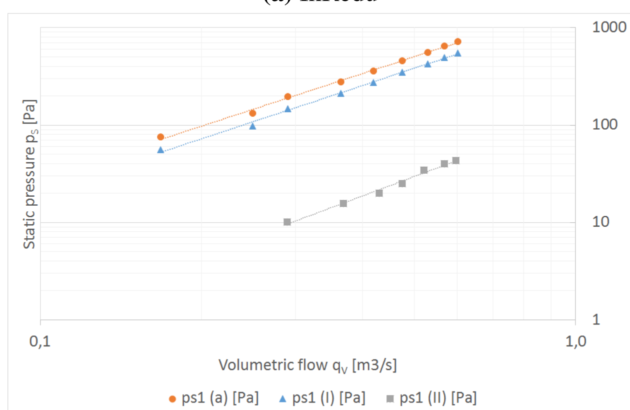
Sample	Method	$\xi_{csn}[-]$	diff $[-]$
Sample2	InRedu	2,519	0,073
	FanRedu	2,446	

Table 7: Minimal and maximal Reynolds number for sample2 for discharge pressure

Sample	Method	Re min $[-]$	Re max $[-]$
Sample2	InRedu	172 029	250 848
	FanRedu	110 431	253 610



(a) InRedu



(b) FanRedu

Figure 7: Loglog plots for Sample2 by discharge pressure

in figure 7, the results are in table 6.

From the graph is obvious that all the measurement were performed for static pressure higher than $10Pa$ which is in accordance with ISO 7235 where in ANSI/ASHRAE Standard 120-2008 is no such restriction. [6] [10]

4 Conclusion

The purpose of the paper was to evaluate and outline three ways of measurement for HVAC equipment at the suction and discharge part of fan. Comparison of friction coefficient calculation by standard ISO 7235 was presented as well. Three types of air flow control options were compared with three types of different samples. Each sample had diverse construction thus results have broad meaning. This leads to necessity for wide meassurement of different speciments to make statistical conclusions for selection of the best flow controling options for meassurement. Also, the extensive numerical simulation by CFD and comparison with physical measurements will be realized in the future.

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